ROAD NOISE GENERATED BY CONCRETE BLOCK PAVEMENTS

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AN IMPORTANT NOTE FOR THE READER

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EXECUTIVE SUMMARY

Introduction

The use of concrete block pavers as a road surfacing in residential and industrial areas is increasing in New Zealand. This has raised concerns regarding the noise levels generated by vehicles travelling over such surfaces.

A study involving continuous and A-weighted ⅓ octave band spectral analysis of tyre-road noise was therefore undertaken in 1992 to highlight differences between pavers and to identify prevalent noise-generating mechanisms. It investigated the relationship of road noise generated from concrete block pavements to the paver size, shape, spacing and chamfer angle, and laying patterns. Four concrete block pavements were selected in residential areas of Rotorua and Auckland, New Zealand. The information gained will be applied to develop a design guide for laying concrete block pavers so that tyre noise generation on such road pavements are reduced.

Methodology

Vehicle exterior and interior noise data, and vertical axle and body accelerations, were recorded for three vehicle speeds (30, 45, 60 km/h) on four study sections constructed of concrete block pavers. The data records were digitised to provide time history records, and axle and body accelerations were converted to vibration velocities. Continuous and ⅓ octave spectral analysis techniques were applied to the exterior and interior noise, and to vibration velocity data, in order to:

- Assess overall noise levels and their variation with speed.
- Generate continuous and ⅓ octave spectral plots for comparison between sites.
- Identify differences in sound levels between the sites in the frequency ranges attributable to the paver size, shape and spacing, and to assess the significance of any differences with respect to the overall sound level of the signal.

Conclusions

The range of interior noise levels across the four pavements was 1.6 dB(A) or less over the three vehicle speeds. In contrast, the range of exterior noise levels was much higher, at 7.2 dB(A) over all speeds.

Exterior noise levels were much higher than those measured inside. Both interior and exterior noise levels increased approximately linearly with increased speed, with the exterior level increasing much faster for the same change in speed. The A-weighted levels were consistent with values measured in countries other than New Zealand.

Peaks associated with the paver size and spacing were identified in the frequency spectra. However, they did **not** dominate either the vehicle interior, or exterior, A-weighted noise spectra. Differences in the sound levels associated with these specific peaks did not contribute significantly to the differences in overall sound levels (7.2 dB(A) in exterior noise) between the sites.

Recommendations
To develop a design guide for laying concrete block pavers so that tyre noise generation is reduced, the dependence of noise on the paver size, spacing and chamfer angle will need to be established and the contribution of surface texture assessed.

To do this, numerical modelling methods should be employed to determine relative noise levels generated by concrete block pavement profiles, covering a range of sizes, shapes, spacings and chamfer angles. The theoretical results should be backed up with a limited range of vehicle-based noise measurements made on selected pavement sections.

ABSTRACT

The use of concrete block pavers as a road surfacing in residential and industrial areas is increasing in New Zealand. This has raised concerns regarding the noise levels generated by vehicles travelling over such surfaces.

A study involving continuous and A-weighted ⅓ octave band spectral analysis of tyre-road noise was therefore undertaken, in 1992, to highlight differences between pavers and to identify prevalent noise-generating mechanisms. Recordings of vehicle exterior and interior noise data, together with vertical axle and body accelerations, were made for three vehicle speeds (30, 45, 60 km/h) on four concrete block pavements selected from residential areas in Rotorua and Auckland, New Zealand. They were subsequently analysed. The resulting noise and acceleration spectra, and recommendations for future investigations, are summarised in this report.

1. INTRODUCTION

Use of concrete block pavers

The use of concrete block pavers as a road surfacing material in residential and industrial areas is increasing in New Zealand. This has raised concerns regarding the noise levels generated by vehicles travelling over such surfaces.

A wide range of concrete block paver shapes, surface textures, and laying patterns is currently used in New Zealand. However, limited information is available on the noise levels that these different possible configurations can produce. As a consequence, research was carried out in 1992 to investigate these noise levels, measuring exterior and interior noise levels on four different concrete block pavement sections in residential areas of Auckland and Rotorua, New Zealand.

Sources of vehicle noise

Studies reported in the literature show that most vehicle noise is generated by two mutually independent sources:

1. the production and application of propulsive power, i.e. engine noise, intake and exhaust noise, and transmission noise; and
2. the forward motion of the vehicle, i.e. wind and road-tyre interaction noise.

Propulsion system noise depends on the vehicle engine speed in each gear. Tyre noise results from the interaction of the tyres with the road surface. It is caused by a combination of tyre carcass vibration and the entrapment and subsequent release of air from the tread cavities. Therefore, road-tyre sound levels are related to the vehicle speed, the type of tyre (tread and construction type), and characteristics of the road surface.

At low speeds the total noise level is dominated by the contribution from the propulsion system, but above a certain critical speed the tyre noise becomes predominant.

Considerable differences exist between noise measured inside and outside road vehicles. Noise generated by a vehicle passes through the body surfaces into the interior. The body surfaces tend to filter out or reduce the contribution of some frequency components to the overall interior noise. Exterior noise is not affected in this way. However, factors of distance, wind speed and direction, and background noise play important roles.

For measurements of vehicle noise levels carried out on level roads at the same speeds, with calm wind conditions and little background noise, the differences (if any) in noise levels between the road surfaces would be caused primarily by the interaction of road and tyres. On roads constructed from concrete block pavers, the road-tyre interaction noise would include components associated with the joints between the pavers and the texture and porosity of the pavers themselves.

Consequently, there appears to be considerable scope for looking at ways to minimise the noise levels associated with this type of road surface.

2. BACKGROUND

2.1 Recent Research

At the 4th International Conference on Concrete Block Paving held in Auckland in 1992, Cenek et al. (1992) reported that, for five New Zealand concrete block pavements investigated, interior noise levels appeared strongly correlated to the degree with which vertical axle vibrations are transmitted to the vehicle body. However, as actual noise signals were not recorded, spectral analysis techniques could not be used to identify the mechanisms responsible for the noise generated by different pavement sections.

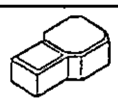
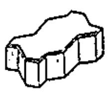
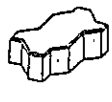
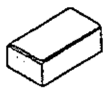
2.2 Concrete Block Pavements

Concrete block pavers used in New Zealand are typically 0.20-0.25 m long and 0.10-0.14 m wide. When laid in a 45° herringbone pattern, the joint spacing in the vehicle wheelpath can range from 0.04 m to 0.16 m, the larger spacing being predominant. Thus, the herringbone pattern would be expected to cause vibrations over spatial frequencies ranging from about 6.3 to 25 cycles per metre. The size of the pavers fixes the location of the spectral peaks, while the gaps between the pavers, sharpness of the paver edges and filling between the pavers affects the levels of the fundamental spectral peaks and their associated harmonics.

2.3 Pavement Study Sections

Four of the five concrete block pavement sections investigated by Cenek et al. were selected for this investigation: Barraud Place in Rotorua, Lakewood Crescent, Ferntree Terrace and Nandina Avenue in Auckland. The details of each section are summarised in Table 2.1, with photographs in Figure 2.1.

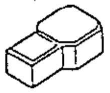
Table 2.1 Details of concrete block pavement study sections.

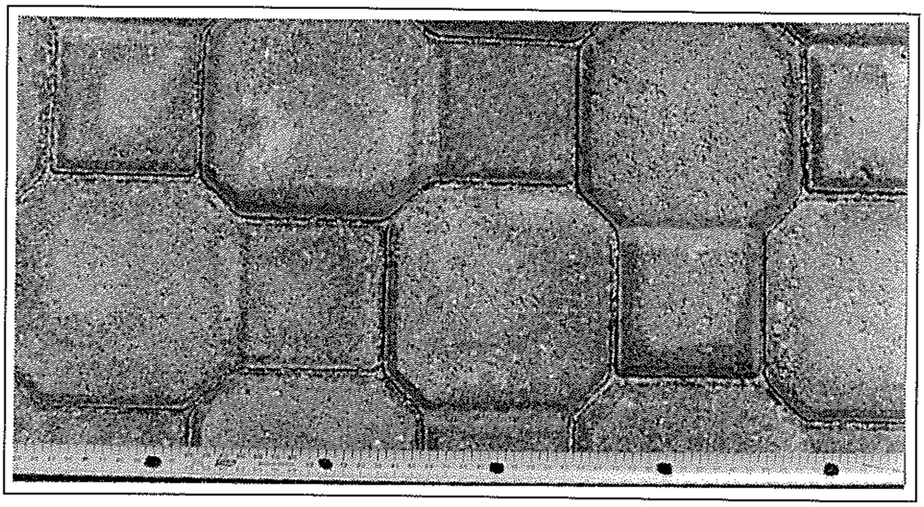
Study Section	**Age** (y*)	**Length** (m)	**Paver Type**	**Chamfer** (°)**	**Joint Width** (mm)**	**Appearance**
Barraud Place	<1	150		35	3	Sharp edges, clean gaps
Lakewood Crescent	6 to 7	150		45	5	Gaps filled with debris, chamfer clearly visible
Nandina Avenue	6 to 7	270		18	2	Edges well rounded, clean gaps
Ferntree Terrace	~1	100		45	3	Sharp edges, clean gaps

(*) estimated age when data were recorded; ** estimated

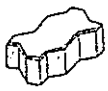
Figure 2.1 Concrete block pavements used as study sections (details in Table 2.1).

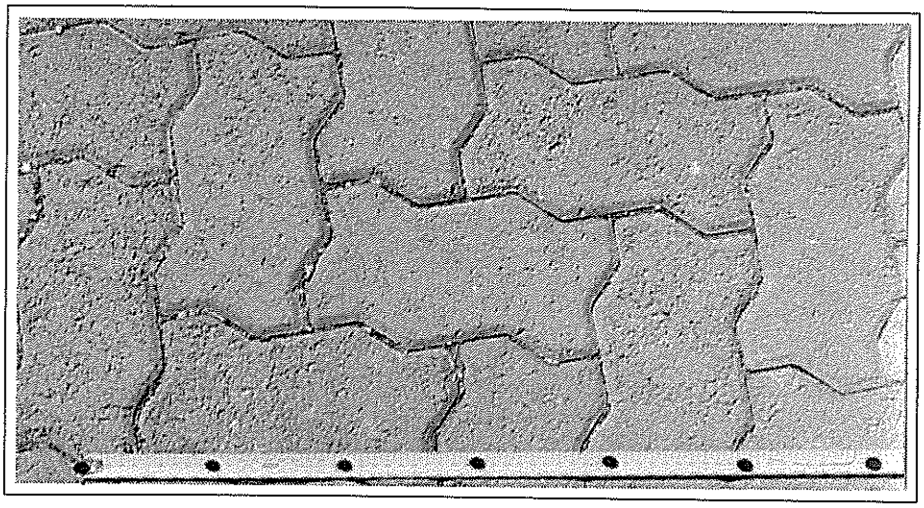
Barraud Place, Rotorua,
with Firth's Keystone pavers



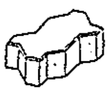


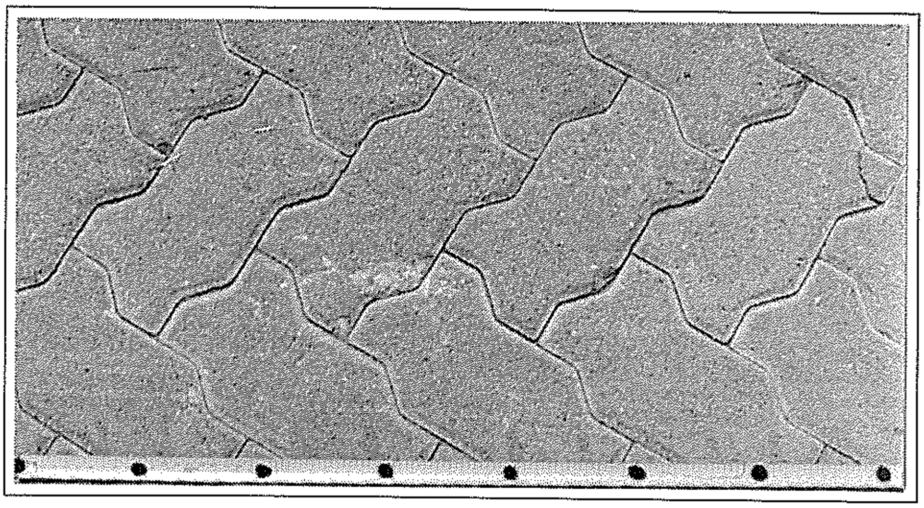
Lakewood Crescent, Auckland,
with Firth's Stockholm pavers



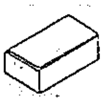


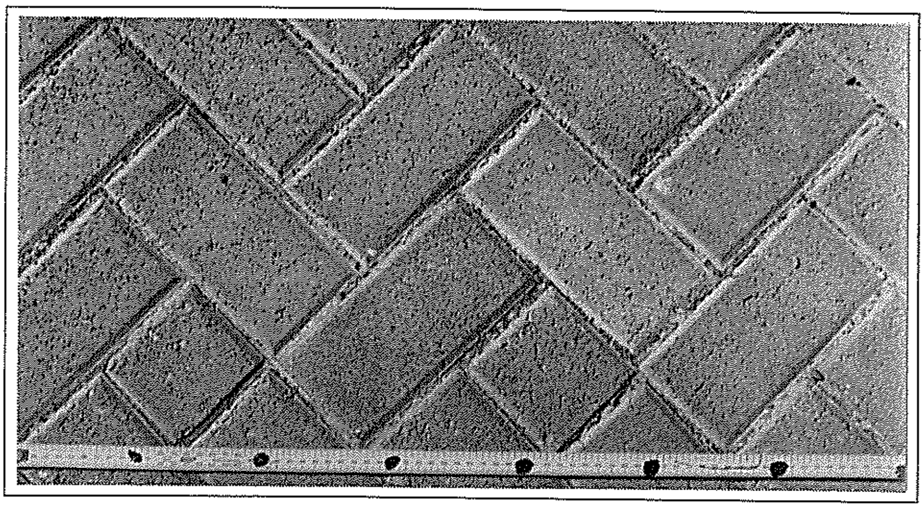
Nandina Avenue, Auckland,
with Firth's Stockholm pavers





Ferntree Terrace, Auckland,
with Firth's Holland pavers





Scale marks are at 10 cm (100 mm) intervals

3. EXPERIMENTAL METHODOLOGY

3.1 Survey Vehicle

The four concrete block pavement sections were surveyed using the Opus Central Laboratories NAASRA roughness vehicle. This was a VN Holden Commodore station wagon that was fitted with a response type meter designed to determine the road roughness in counts/km.

3.2 Instrumentation

3.2.1 Vertical Acceleration

Two Bruel and Kjaer accelerometers were fitted to the vehicle to measure vertical accelerations. One was mounted on the rear axle housing and the other on the vehicle body next to the NAASRA roughness meter. The accelerometers had a flat response from 0.2 Hz to 10 kHz.

3.2.2 Interior Noise

A Rion NL10 sound level meter was installed in the NAASRA roughness vehicle. It was centrally mounted at ear level over the front passenger seat. The output signal was a voltage that corresponded to an "F weighted" or "flat" response (Appendix 1).

The signals from the accelerometers and the sound level meter were simultaneously recorded on a multi-channel FM tape recorder. A tape speed of 9.5 cm/s was used to enable spectral analysis to be performed at a later stage.

3.2.3 Exterior Noise

A Quest 2400 sound level meter was used for the exterior noise measurements. This was set up according to guidelines given in NZS 6801:1977 (SANZ 1997). The instrument was located approximately 4 m away from the path of the test vehicle, at 1.2 m above ground level. The output from the sound level meter was a voltage that corresponded to a "C-weighted" response (Appendix 1). This is an approximately unweighted response. The sound level signal was recorded on a portable tape-recorder.

3.3 Test Procedure

The test vehicle was driven over each road section at three different speeds (30 km/h, 45 km/h and 60 km/h), repeated at least twice at each speed. Recordings of the vertical axle and body accelerations and the interior and exterior noise levels were made for each run. In addition, the "F-weighted" (interior) and "C-weighted" (exterior) equivalent sound level readings L_{eq}(dB) were monitored. Records of weather conditions, wind speed and atmospheric pressure were also made.

4. SPECTRAL ANALYSIS

4.1 Background

To handle a set of random vibrations, e.g. noise level and acceleration signals, the power spectrum must be considered over the entire frequency range of vibrations being produced. Essentially a power spectrum of any signal provides a measure of the relative contributions made by different frequencies to the overall energy content of the signal.

By analogy with probability and probability density, a power spectral density (PSD) is defined, where PSD is the power per unit frequency over the frequency range. The PSD function of a measured parameter is the variance of the parameter divided by the spatial frequency of the measured parameter. For a finite and statistically constant total power input, the PSD may be used to estimate the proportion of the power being applied to each frequency range. Power spectra can be based on a continuous frequency distribution or, as is more usual in acoustics, the frequencies can be grouped into octave or ⅓ octave bands (Appendix 1).

4.2 Sound Level Weightings

Human hearing is not equally sensitive to all frequencies. The apparent loudness of a sound varies with frequency as well as sound pressure, and the variation of loudness with frequency also depends to some extent on the sound pressure. Sound measuring instruments are now designed with electronic "weighting" networks to make allowances for the responses of the ear. The "A-weighting" was originally designed to approximate the response of the human ear at low sound levels (Appendix 1).

4.3 Noise and Vibration Velocity Data

Continuous and ⅓ octave bandpass exterior and interior noise spectra were computed for the three speeds (30 km/h, 45 km/h and 60 km/h) for each of the four study sections. Overall A-weighted sound levels were calculated by applying a correction to each frequency band, and then summing the individual contributions. For the exterior noise the peak section of the record needed to be determined statistically. Continuous vibration velocity spectra were also computed. Because the sound level meter and accelerometer signals were processed with the same gain for all the test sections, the spectra for the different road surfaces can be directly compared, e.g. all of the interior noise spectra can be compared, or all of the body vibration velocity spectra.

Only intermittent axle acceleration signals were recorded for Barraud Place, Lakewood Crescent and Nandina Avenue, because of an instrument malfunction thought to have been caused by water spray. These signals were not of sufficient length for a spectral analysis. However, the instrumentation was performing correctly for the Ferntree Terrace measurements, when full axle acceleration traces were recorded.

5. RESULTS

5.1 Overall A-Weighted Noise Levels

The overall A-weighted exterior and interior noise levels calculated from the ⅓ octave bandpass analysis are listed in Table 5.1 and plotted in Figures 5.1 and 5.2 as functions of speed. Also included in Table 5.1 for reference are the corresponding equivalent sound levels (L_{eq}) that were measured and recorded on site.

Table 5.1 Exterior and interior noise levels calculated from ⅓ octave bandpass analysis for the study sections.

Study Section	Speed (km/h)	Exterior Noise Level		Interior Noise Level	
		dB(A)	L_{eq}(C)	dB(A)	L_{eq}(F)
Barraud Place	30 45 60	74.4 77.4 85.0	75.7 76.7 83.9	62.9 65.7 66.9	98.5 101.3 102.3
Lakewood Crescent	30 45 60	71.5 75.2 81.2	79.3 80.4 81.5	64.1 65.8 67.2	103.3 105.1 105.6
Nandina Avenue	30 45 60	77.4 82.4 86.5	78.7 80.1 80.7	63.0 64.5 66.8	100.2 102.4 103.2
Ferntree Terrace	30 45 60	74.7 80.3 84.6	78.7 80.7 84.1	62.5 65.0 67.8	98.0 101.9 101.6

Note that the overall A-weighted exterior noise levels may in some cases be higher than the L_{eq} values. The difference is because the A-weighted values were calculated by statistically determining the peak section of the record, and the manually timed L_{eq} values were recorded when the tests were performed.

5.2 ⅓ Octave Bandpass Noise Spectra

Over the range of the three test speeds, the exterior and interior A-weighted noise levels show differences of approximately 8 dB(A) and 2 dB(A) respectively (Table 5.1, Figures 5.1 and 5.2). To determine whether there were any significant differences in the frequency content for each site, plots of the unweighted and A-weighted ⅓ octave bandpass spectra were generated. Exterior and interior noise level data for the two sites showing the most significant differences in overall sound levels, i.e. Lakewood Crescent and Nandina Avenue, are shown in Figures 5.3 and 5.4. In each of the figures, the data are plotted as the magnitude of the noise level associated with each ⅓ octave band at the centre band frequency. The calculated frequency ranges of the likely fundamental spectral peaks associated with the joint spacing between the concrete pavers have been marked on the plots as two vertical lines. An entire set of the spectra is presented in Appendix 2.

Figure 5.1 Variation of overall sound levels with speed for exterior noise.

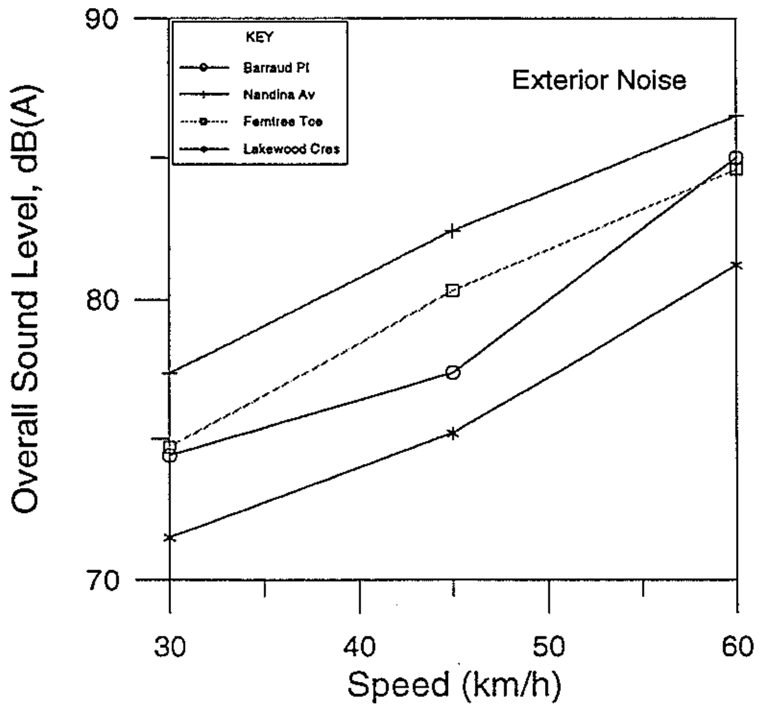


Figure 5.2 Variation of overall sound levels with speed for interior noise.

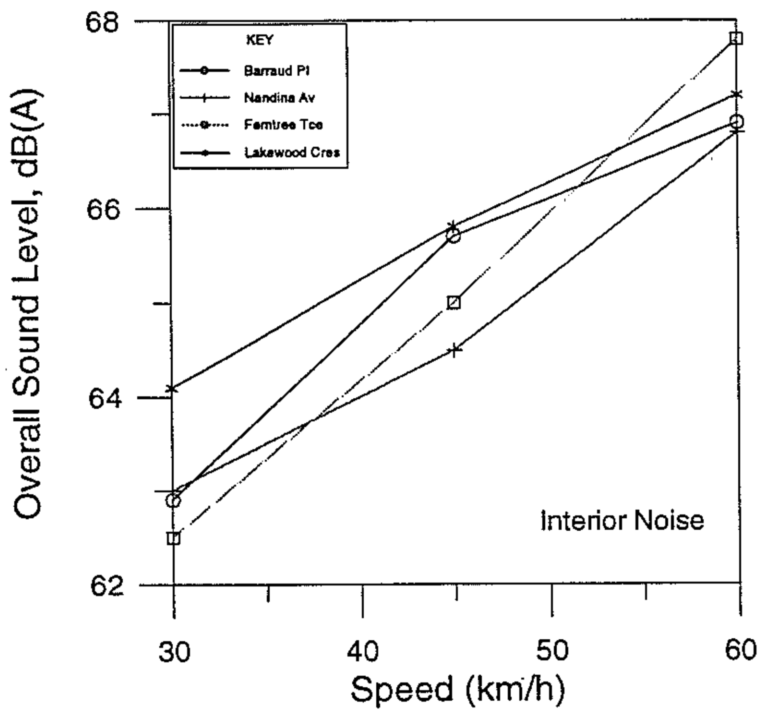


Figure 5.3 Exterior noise with ⅓ octave bandpass spectra for Lakewood Crescent and Nandina Avenue. (See Appendix 2 for full set of spectra.)

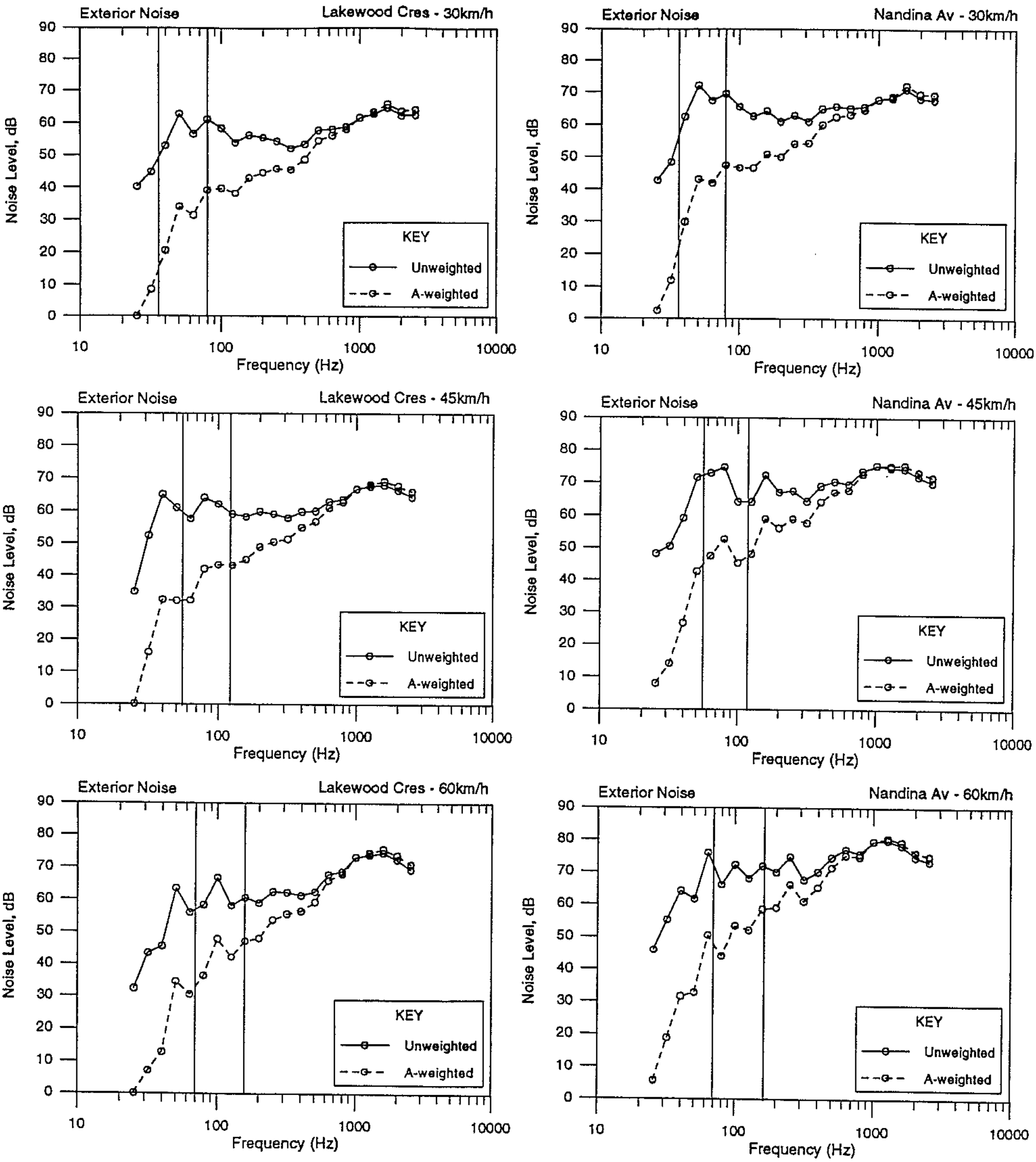


Figure 5.4 Interior noise with ⅓ octave bandpass spectra for Lakewood Crescent and Nandina Avenue. (See Appendix 2 for full set of spectra.)

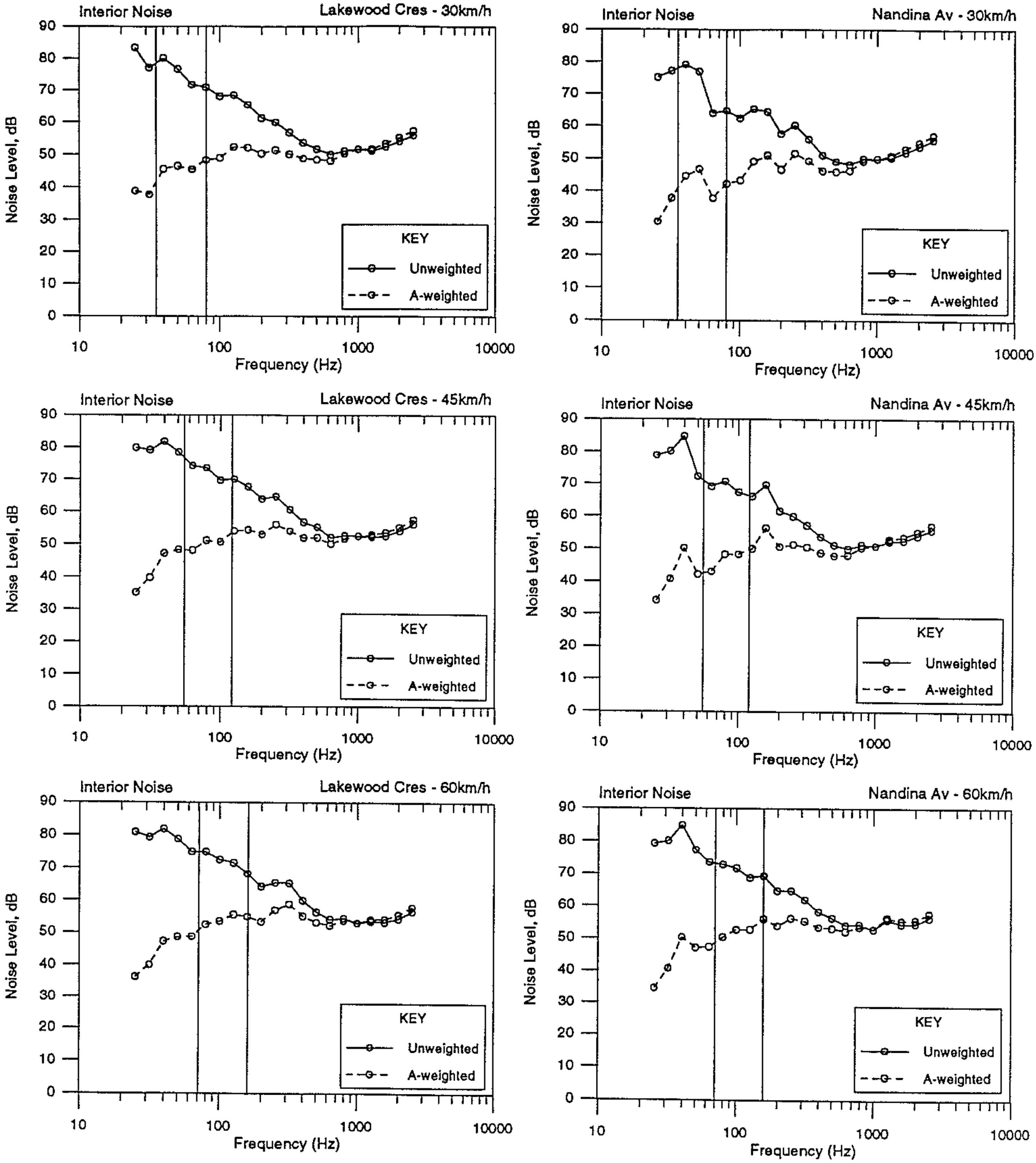
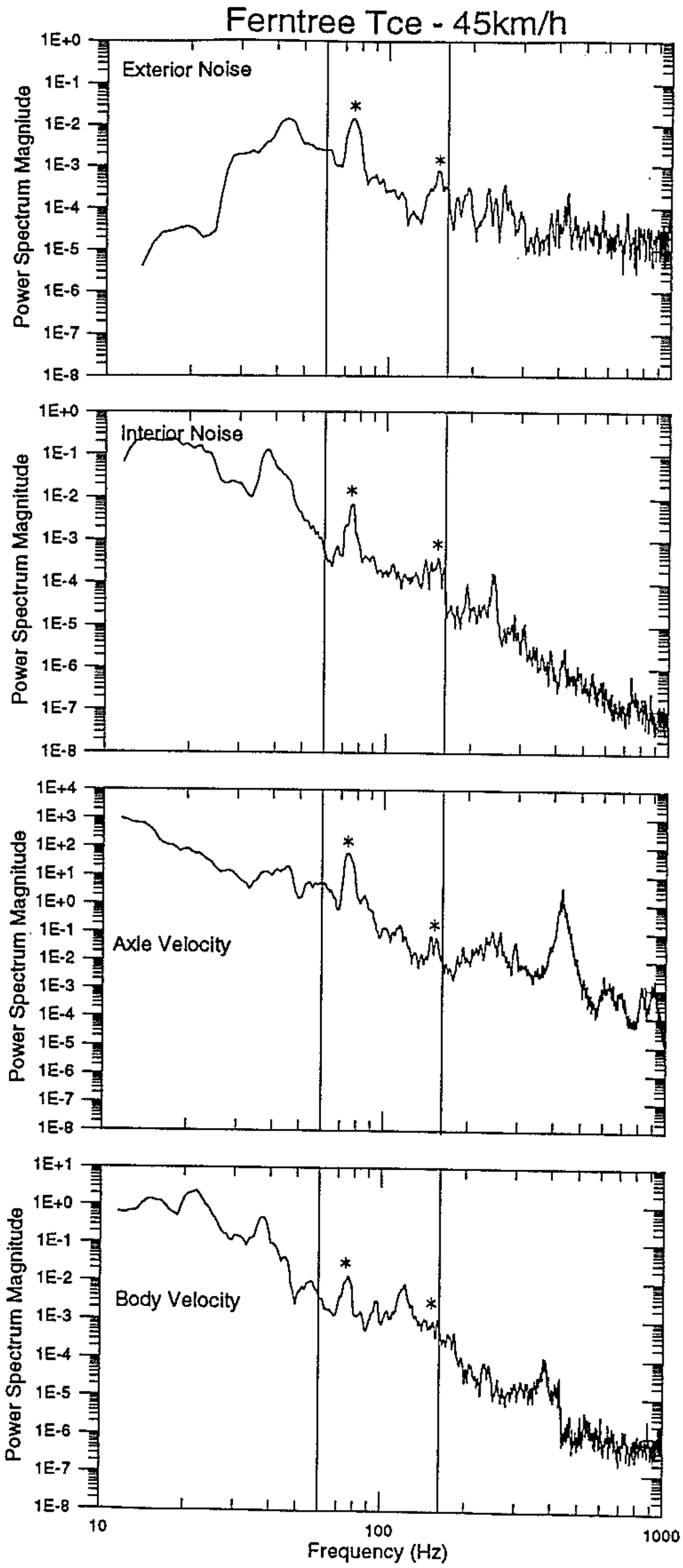


Figure 5.5 Continuous frequency spectra for Ferntree Terrace and a vehicle speed of 45km/h. (See Appendix 3 for full set of frequency spectra.)

* Spectral peak associated with dimensions of the pavers.



5.3 Continuous Frequency Spectra

Continuous frequency unweighted noise and vibration velocity spectra were generated to determine if any dominant frequency peaks attributable to the paver size or spacing could be identified. The spectra for Ferntree Terrace for a vehicle speed of 45 km/h are shown in Figure 5.5. A full set of spectra is presented in Appendix 3.

Given the sizes of the pavers, a range of frequencies over which fundamental spectral peaks caused by the pavers would be expected to occur can be calculated. This frequency range and the frequencies of the peaks present in the spectra will depend on the speed of the vehicle and the direction of travel in relation to the orientation of the blocks.

In Figure 5.5, the frequency range of the likely fundamental spectral peaks associated with the dimensions of the concrete pavers relative to the direction of travel is shown by two vertical lines, and the two fundamental spectral peaks associated with the length and width dimensions of the concrete pavers are marked with asterisks "*".

6. DISCUSSION

6.1 A-Weighted Noise Levels

6.1.1 Exterior Noise

The overall A-weighted exterior noise levels presented in Table 5.1 and Figure 5.1 show similar trends at each of the three test speeds, as follows:

- Noise levels increase in an approximately linear way by 3.0 to 3.5 dB(A) per 10 km/h increase in vehicle speed, for all four test sites.
- Nandina Avenue is consistently the noisiest of the surfaces, whereas Lakewood Crescent is the quietest. The other two surfaces had very similar noise levels at speeds of 30 km/h and 60 km/h, but Ferntree Terrace was noticeably noisier at 45 km/h.
- At each of the three test speeds the difference between the quietest and the noisiest surface was around 5 to 7 dB(A).

Both the noisiest and quietest of the four surfaces are comprised of the same paver shape (i.e. Firth Stockholm pavers). Several possible reasons for the differences measured include: (1) background noise, (2) different surface textures, and (3) the effects of different chamfer angle and joint spacing (Table 2.1), and (4) the direction of travel with respect to orientation of the pavers. Unfortunately, measurements of the background noise and surface texture were not made.

6.1.2 Interior Noise

The overall A-weighted exterior noise levels presented in Table 5.1 and Figure 5.1 show that:

- Noise levels increase in an approximately linear way by 1.0 to 1.8 dB(A) per 10 km/h increase in vehicle speed, for all four study sites; this is a much smaller increase than measured for the exterior noise.
- In contrast to the exterior noise, Lakewood Crescent is generally noisier than Nandina Avenue.
- Significantly less variation (less than 2 dB(A)) was recorded for each test speed, across the four study sites, than for the exterior noise levels. The noise levels are consistent with the results of similar measurements made in Australia (Samuels and Sharp 1985).

6.2 ⅓ Octave Bandpass Noise Spectra

The ⅓ octave bandpass noise spectra presented in Section 5.2 of this report show that neither the interior nor the exterior noise spectra are dominated by any fundamental frequencies in the ranges expected to be related to the paver size or spacing. Both the exterior and interior A-weighted noise spectra are dominated by higher frequencies, although the contributions to the interior noise from the lower frequency bands are greater than they are to the exterior noise. This indicates that the components of interior noise related to the concrete block pavers were largely masked by existing levels of low frequency noise such as engine and exhaust noise.

Despite this masking effect, the frequency selective human ear can usually pick out the discrete frequency peaks of these components. Therefore vehicle passengers and outside observers may notice the noise components associated with the concrete block pavers.

6.3 Continuous Frequency Spectra

The continuous frequency noise and vibration velocity spectra do show the presence of discrete frequency peaks within the expected ranges calculated from the sizes of the paver blocks. Furthermore, harmonics of these peaks are also present. However, the relatively small differences in the A-weighted interior sound levels across the four study surfaces suggest that neither the fundamental peaks nor their harmonics make significantly different contributions to the overall sound levels.

7. CONCLUSIONS

The primary research objective was to establish, using spectral analysis, the dependence of road noise generated by four selected concrete block pavements on the paver size, spacing and laying pattern. From analysis of exterior and interior noise signals, and vehicle body and axle acceleration signals, the following conclusions have been drawn.

7.1 Sound Level Measurements

1. The A-weighted sound levels increased as an approximately linear function of vehicle speed (interior - 1.0 to 1.8 dB(A) / 10 km/h, exterior - 3.0 to 3.5 dB(A) / 10 km/h), with much higher exterior sound levels than interior sound levels.

2. The range of exterior A-weighted sound levels across the four study sites was 7.2 dB(A) at each of the three vehicle speeds, with differences between the sites spread over a wide frequency range.

3. The range of interior A-weighted sound levels across the four study sites was 1.6 dB(A) at each of the three vehicle speeds, with differences in sound levels between the sites spread over a wide range of lower frequencies.

7.2 Spectral Analysis

1. No significant differences in the A-weighted noise spectra for the four sites were specifically attributable to differences in the size, shape and laying pattern of the concrete block pavers.

2. Both the exterior and interior A-weighted noise spectra were dominated by frequencies higher than those fundamental frequencies calculated to be caused by the size and laying pattern of the concrete block pavers.

3. A-weighted vehicle interior noise had significantly more low frequency content than the exterior noise.

4. Distinct spectral peaks attributable to paver size and shape were identified in the continuous frequency noise and vibration velocity spectra.

5. The dependence of road noise on the size, shape and laying pattern of the concrete block pavers cannot be established from results for the range of pavers and laying systems investigated in this study. Consequently, recommendations for specific experimental work are given in Section 8 of this report.

8. RECOMMENDATIONS

The relationships between noise levels and concrete paver shape, laying pattern, spacing, and chamfer angle need to be further quantified. The contribution of surface texture of the pavers also needs to be assessed. This information is needed to develop a design guide for laying concrete block pavers so that tyre-noise generation is reduced. These objectives could be achieved using any one of the four options described here.

Option 1 Vehicle-based noise measurements to determine contributions to noise emissions

These measurements would represent an extension to the current study. They would involve the selection of a wider range of paver sizes, spacing and laying patterns. Recordings of the interior and exterior noise and acceleration measurements, together with readings of the corresponding sound levels, would be made in a manner similar to that described in Section 3 of this report. However, the exterior noise would be monitored using a microphone, or several microphones, located close to one of the vehicle wheels to allow more detailed exterior noise spectra to be obtained, and to minimise the effects of background noise.

Specific tests would include:

- Reading and recording background noise levels.
- Recording noise and acceleration signals (plus sound level readings) while the vehicle is stationary and while the engine speed is equivalent to running at the chosen test speeds (to isolate contribution of the engine to the noise signals).
- Recording noise and acceleration signals (plus sound level readings) while the vehicle is coasting (with the engine off) at speeds as close as possible to the three test speeds, to isolate the contributions of the vehicle transmission and the concrete pavers to the noise signals.
- Measurements of surface texture, with a laser profilometer or a mini texture meter, to allow texture effects to be assessed.

The test method proposed would allow the determination of the relative importance of these different contributions to the overall noise in a realistic situation.

Option 2 Trailer-based noise measurements to investigate tyre-road interactions

These measurements would involve the design and construction of a trailer covered with a shroud that would acoustically isolate the interior as much as possible from exterior noise sources. The tyres and suspension of the trailer would have the same characteristics as a vehicle.

Sound level measurements and recordings of noise and axle vibration would be made within the acoustic shroud for different vehicle towing speeds.

This method would eliminate most of the background and vehicle noise and allow the direct determination of the relative effects of paver size, surface texture and laying pattern. However, it does not allow the effect of the vehicle body on noise transmission to be identified.

Option 3 Numerical modelling

Advances in computing and numerical modelling are making possible the use of numerical models to more accurately describe the interaction of tyre and pavement. Recent research (Cenek and Fong 1996) has shown that predictions of relative noise levels can be made based on road profiles that are typically measured with a laser profilometer. An extension of this work would allow the use of simulated road profiles, "fabricated" to investigate the effect of paver spacing and chamfer angle for example.

Option 4 Combination of noise measurements and numerical modelling

A combination of a limited range of vehicle-based noise measurements and numerical modelling would be the most efficient way to obtain the information needed to develop the design guide.

APPENDICES

APPENDIX 1.
SOUND LEVEL METERS: SOUND LEVEL WEIGHTING

This appendix contains a description of sound level meters and the different weightings methods that are commonly used in sound measurements. The information was reproduced from Harris (1979). Also included is a table showing the corrections applicable to the ⅓ octave frequency bands for the different weighting methods.

Sound Level Meter
A sound level meter is an instrument for the measurement of sound level, which is one of the basic measures used to estimate the possible effects of a particular sound or to rate noise sources. A primary function of a sound level meter is to provide a reading that can be used to rank noises in a subjective way.

The principal components of a sound level meter are shown in Figure A1.1. The microphone converts sound waves into an electric signal which is amplified to provide readings on a meter. Usually a control is provided to adjust the range of sound levels that can be read. This control, called an attenuator, serves to reduce the amplification (usually in 10 dB steps) from the maximum provided by the amplifier. This permits the sound level meter to be used for measurements over a wide range of sound levels. Most sound level meters include an output connection which may provide a signal that can be recorded on an auxiliary instrument, such as a tape recorder.

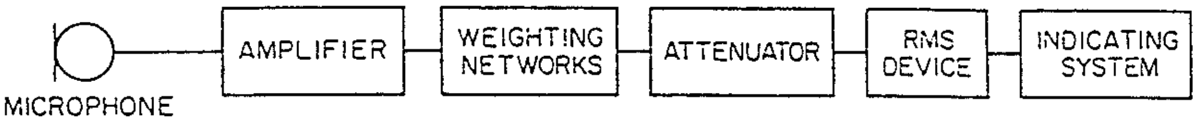


Figure A1.1 Diagram of the principal components of a sound level meter.

Weighting Networks
The sound level reading on a sound level meter for a fixed input level depends on the frequency of the sound from the microphone. If the sound level is independent of the frequency range, the response is described as "flat", because "flat" is descriptive of the graphical representation of the response.

The most widely used weighting is "A-weighting". Its response is a maximum at 2500Hz. Its response drops rapidly as the frequency decreases below 1000Hz and [decreases] gradually as frequency increases above 4000Hz, as shown in Figure A1.2. The unit of A-weighted sound is the decibel, dB. The symbol dB is followed by the letter "A" in parentheses to indicate that the A-weighting has been employed.

The response of the "B-weighting" network as shown in Figure A1.2 is rarely used. The "C-weighting" network is essentially uniform in response from 30Hz to 8000Hz. When all the components of a noise that are of interest are restricted to that range, C-weighting is sometimes used to measure sound pressure level. Some sound level meters include a "flat" response which is often used when the meter supplies a signal to another instrument. Table A1.1 shows the decibel corrections for the various weighting networks from the "flat" values for ⅓ octave bands (listed under the centre band frequency).

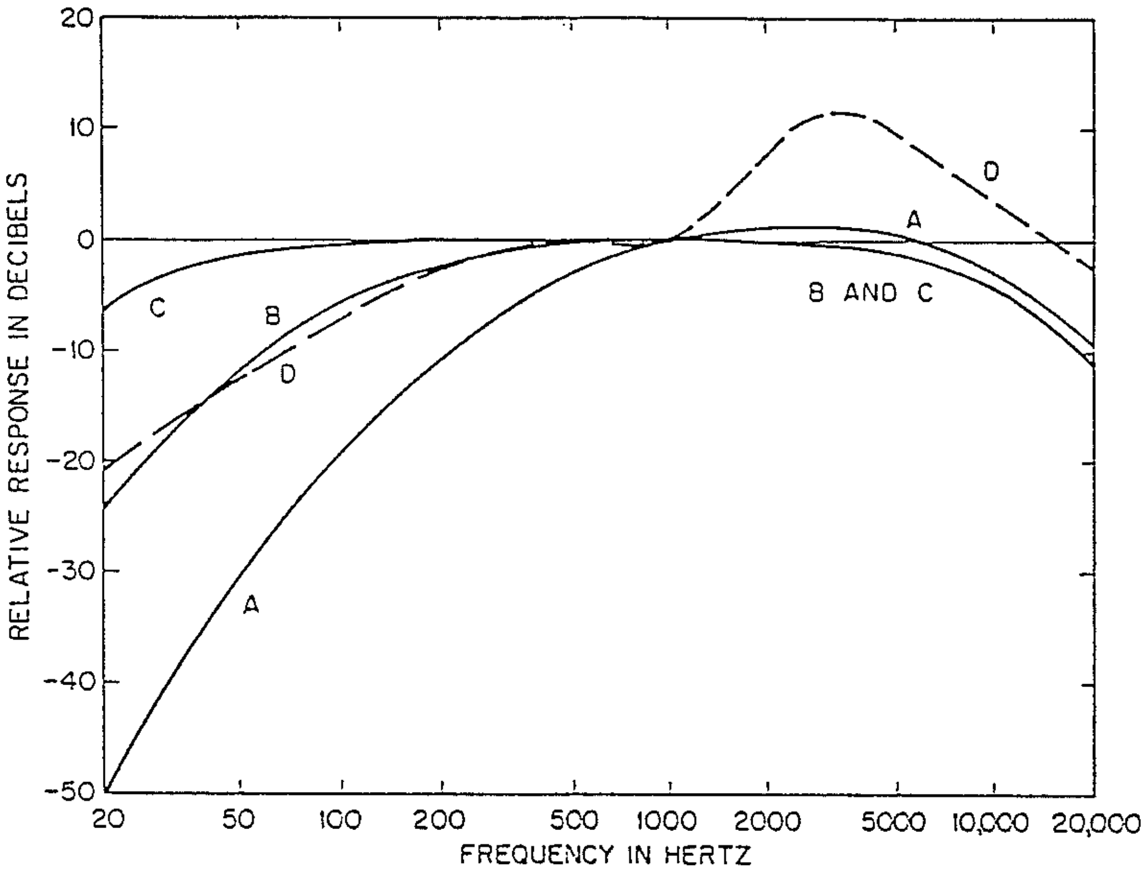


Figure A1.2 Frequency response characteristics of weightings in sound level meters.

Table A1.1 A, B, C and D weightings in sound level meters.

Centre Frequency (Hz)	Correction (dB)			
	A	B	C	D
20	-50.5	-24.2	-6.2	-20.6
25	-44.7	-20.4	-4.4	-18.7
31.5	-39.4	-17.1	-3.0	-16.7
40	-34.6	-14.2	-2.0	-14.7
50	-30.2	-11.6	-1.3	-12.8
63	-26.2	-9.3	-0.8	-10.9
80	-22.5	-7.4	-0.5	-9.0
100	-19.1	-5.6	-0.3	-7.2
125	-16.1	-4.2	-0.2	-5.5
160	-13.4	-3.0	-0.1	-4.0
200	-10.9	-2.0	0.0	-2.6
250	-8.6	-1.3	0.0	-1.6
315	-6.6	-0.8	0.0	-0.8
400	-4.8	-0.5	0.0	-0.4
500	-3.2	-0.3	0.0	-0.3
630	-1.9	-0.1	0.0	-0.5
800	-0.8	0.0	0.0	-0.6
1000	0.0	0.0	0.0	0.0
1250	0.6	0.0	0.0	2.0
1600	1.0	0.0	-0.1	4.9
2000	1.2	-0.1	-0.2	7.9
2500	1.3	-0.2	-0.3	10.4
3150	1.2	-0.4	-0.5	11.6
4000	1.0	-0.7	-0.8	11.1
5000	0.5	-1.2	-1.3	9.6

APPENDIX 2.
⅓ OCTAVE BANDPASS NOISE SPECTRA

Plots of the ⅓ octave bandpass power spectra for interior (Figure A2.1) and exterior (Figure A2.2) noise for the four sites at three speeds are presented on the following pages. The horizontal axis is plotted in terms of frequency, in units of Hz. The vertical axis is plotted in terms of sound level in decibels (dB).

In each of the figures, the expected frequency range associated with the paver size and spacing has been shown by two vertical lines.

Figure A2.1a Interior noise generated by pavers on Lakewood Crescent and Nandina Avenue, at 30, 45 and 60 km/h.

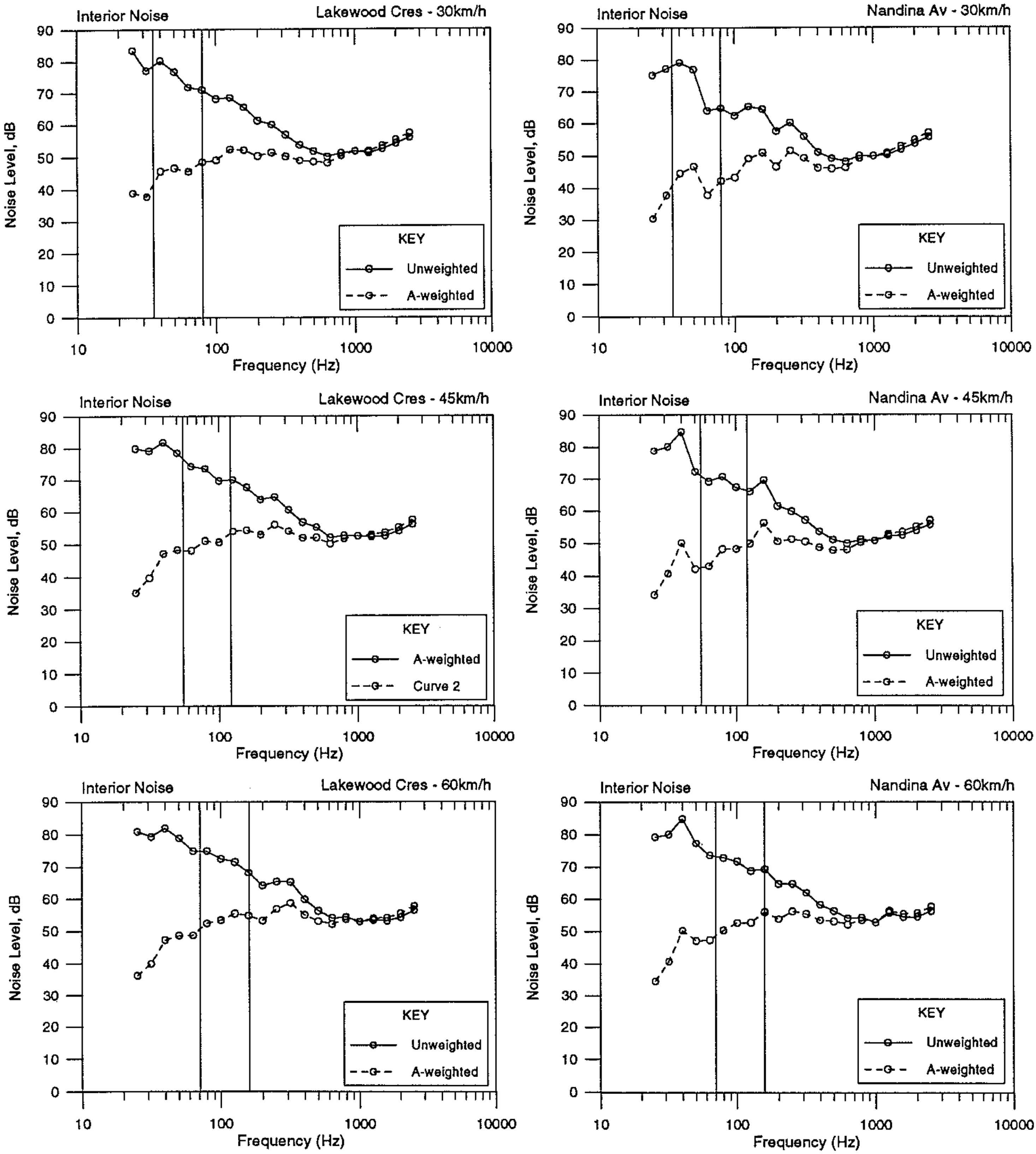


Figure A2.1b Interior noise generated by pavers on Barraud Place and Ferntree Terrace, at 30, 45 and 60 km/h.

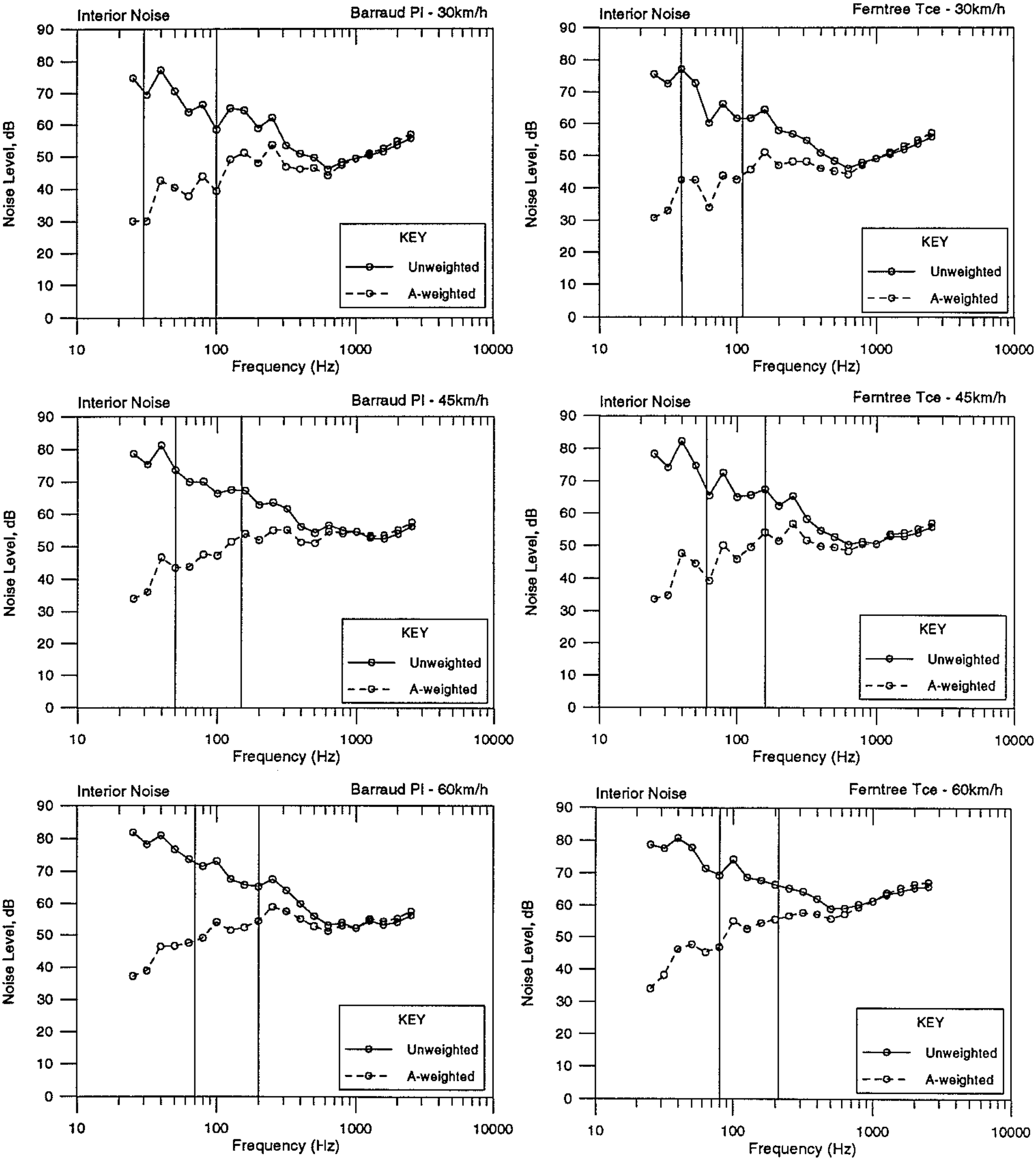


Figure A2.2a Exterior noise generated by pavers on Lakewood Crescent and Nandina Avenue, at 30, 45 and 60 km/h.

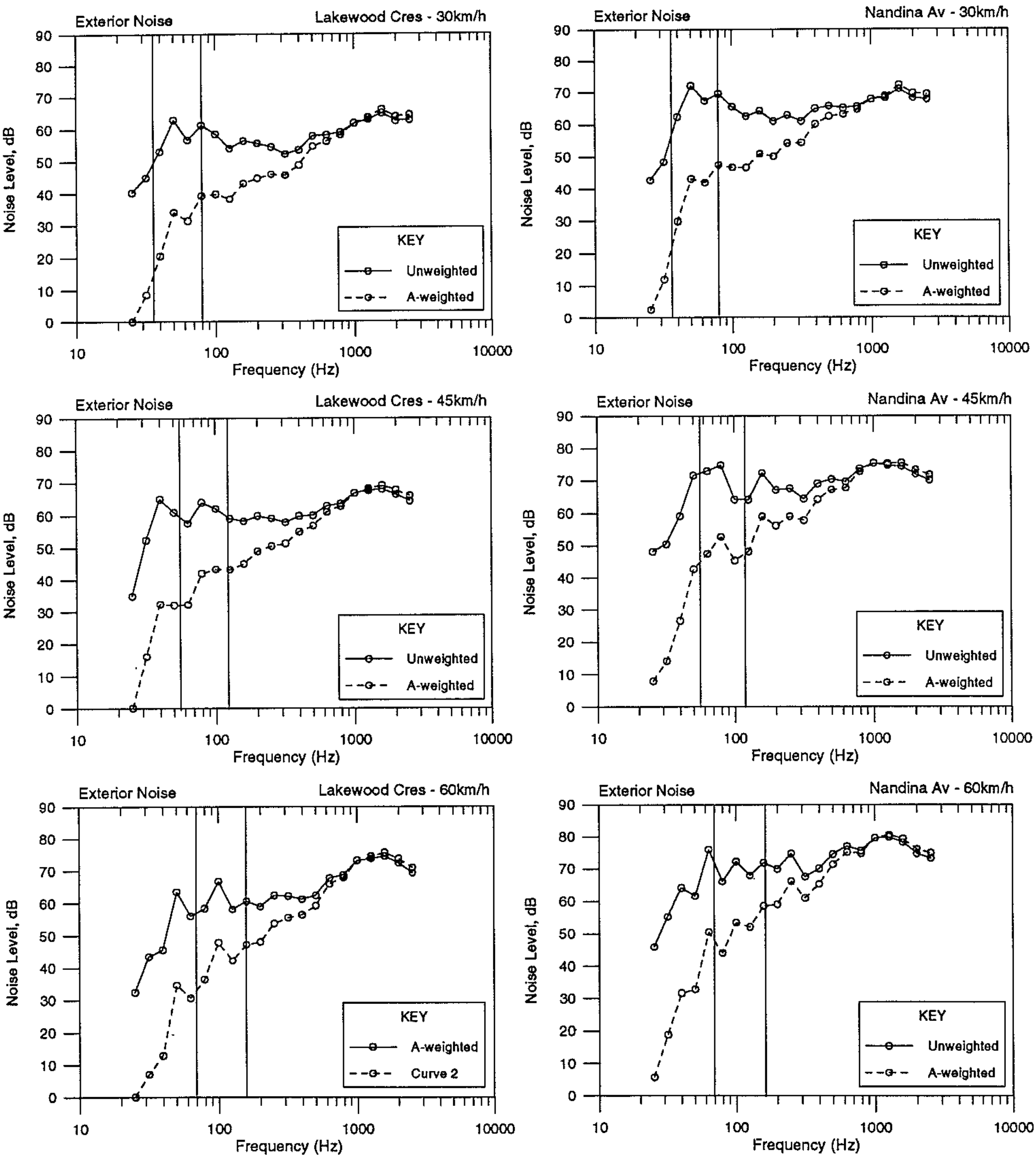
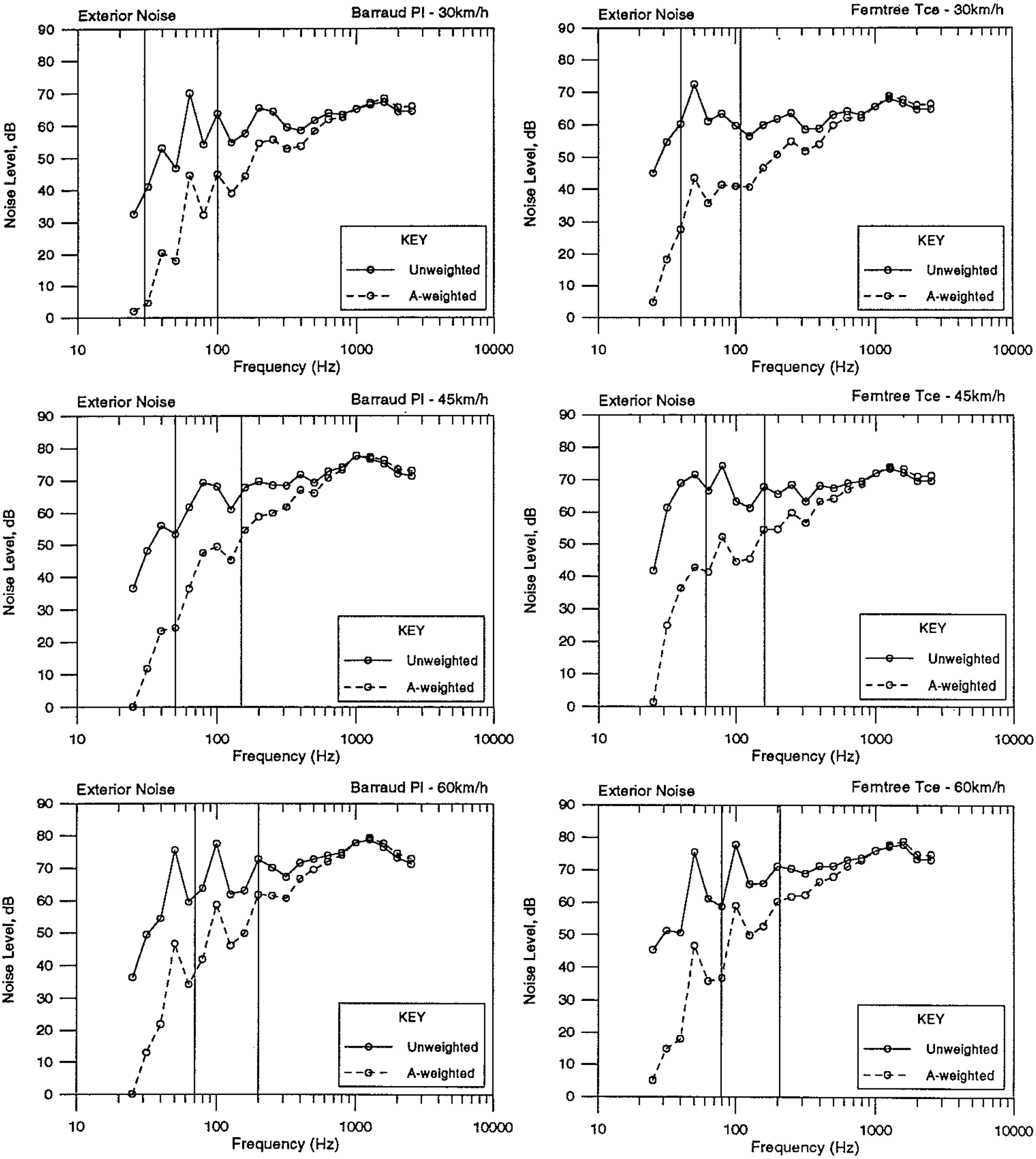


Figure A2.2b Exterior noise generated by pavers on Barraud Place and Ferntree Terrace, at 30, 45 and 60 km/h.



APPENDIX 3.
CONTINUOUS FREQUENCY SPECTRA

Plots of the continuous frequency power spectra for exterior noise, interior noise, axle vibration and body velocities are presented on the following pages. The horizontal axis is plotted in terms of frequency, in units of Hz. The vertical axis is plotted in terms of power spectrum magnitude.

In each of the figures, the calculated frequency range of the likely fundamental spectral peaks associated with the joint spacing between the concrete pavers are shown by two vertical lines, and the fundamental spectral peak/s associated with the joint spacing between the concrete pavers are marked with an asterisk "*".

Figure A3.1 Continuous frequency spectra for concrete block pavers in Barraud Place, Rotorua, for vehicle speeds of 30 km/h, 45 km/h and 60 km/h.

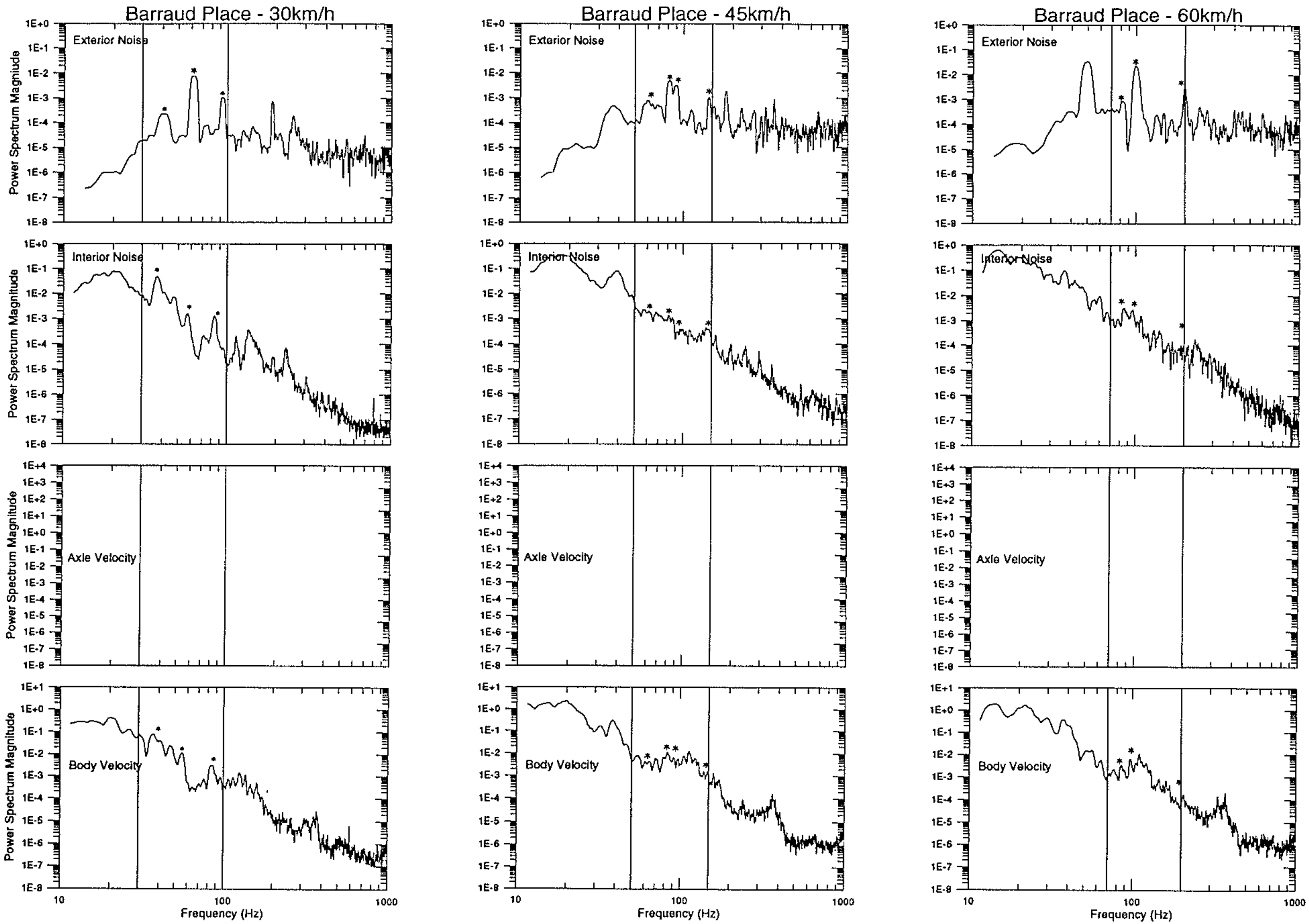


Figure A3.2 Continuous frequency spectra for concrete block pavers in Lakewood Crescent, Auckland, for vehicle speeds of 30 km/h, 45 km/h and 60 km/h.

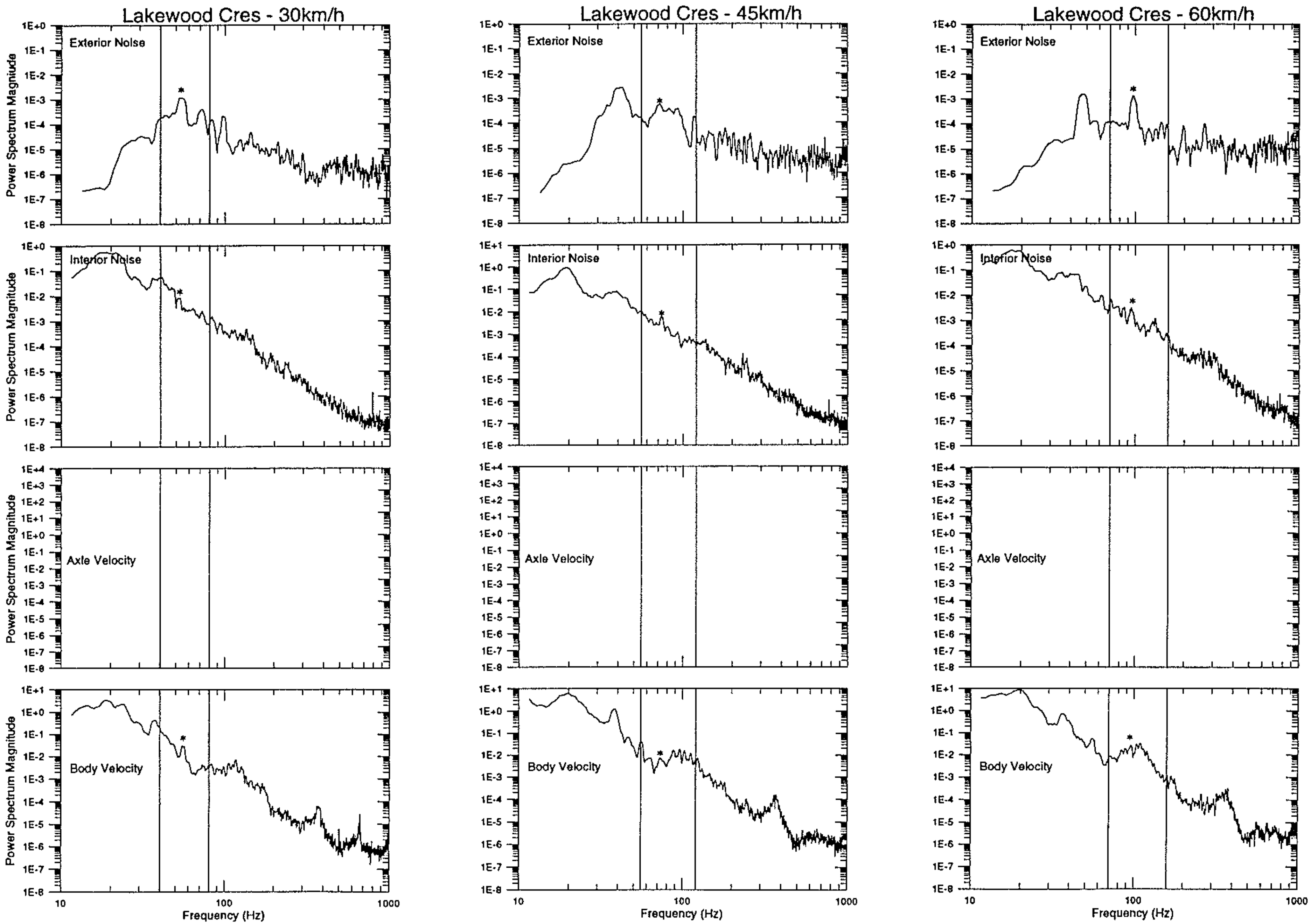


Figure A3.3 Continuous frequency spectra for concrete block pavers in Nandina Avenue, Auckland, for vehicle speeds of 30 km/h, 45 km/h and 60 km/h.

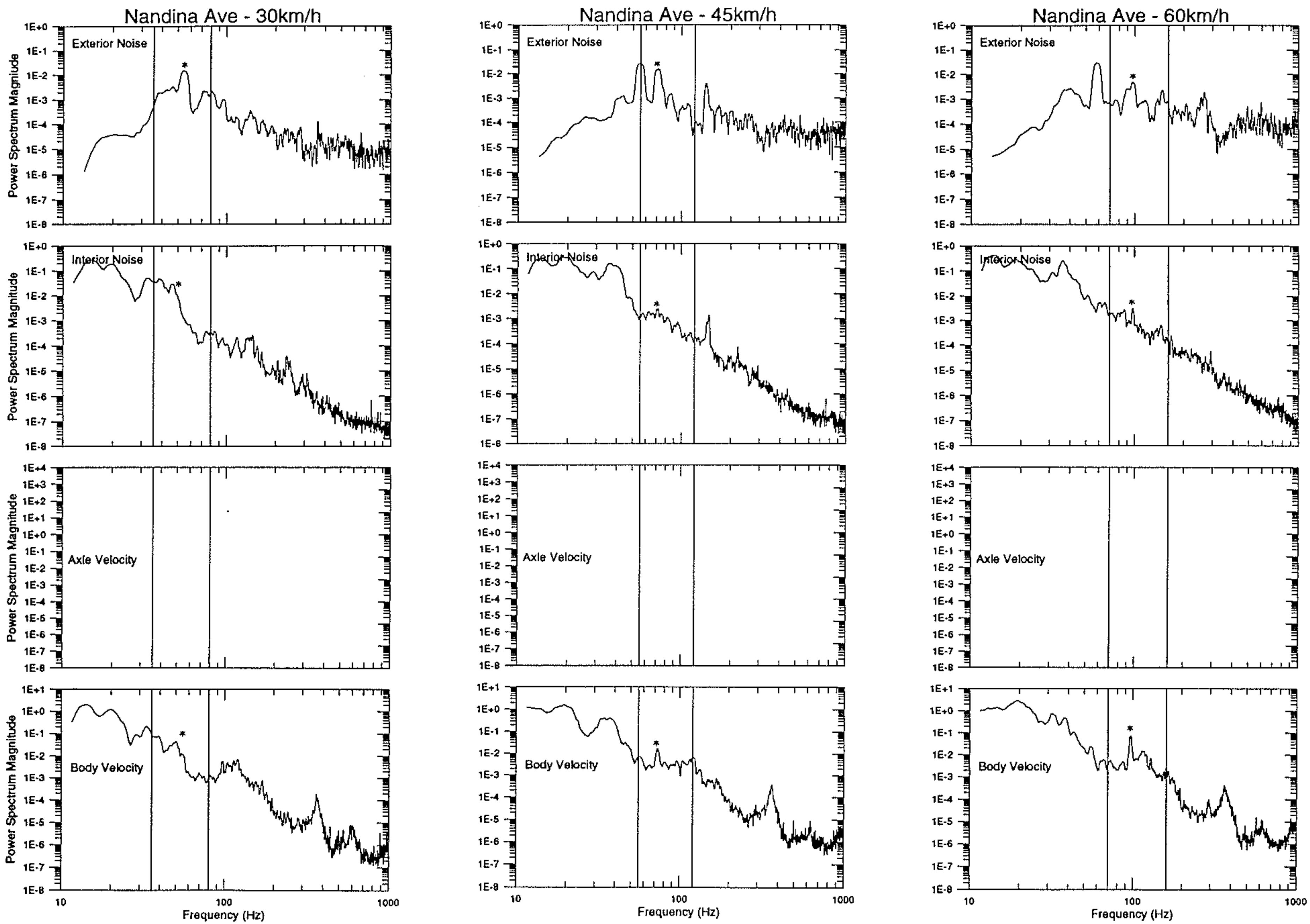
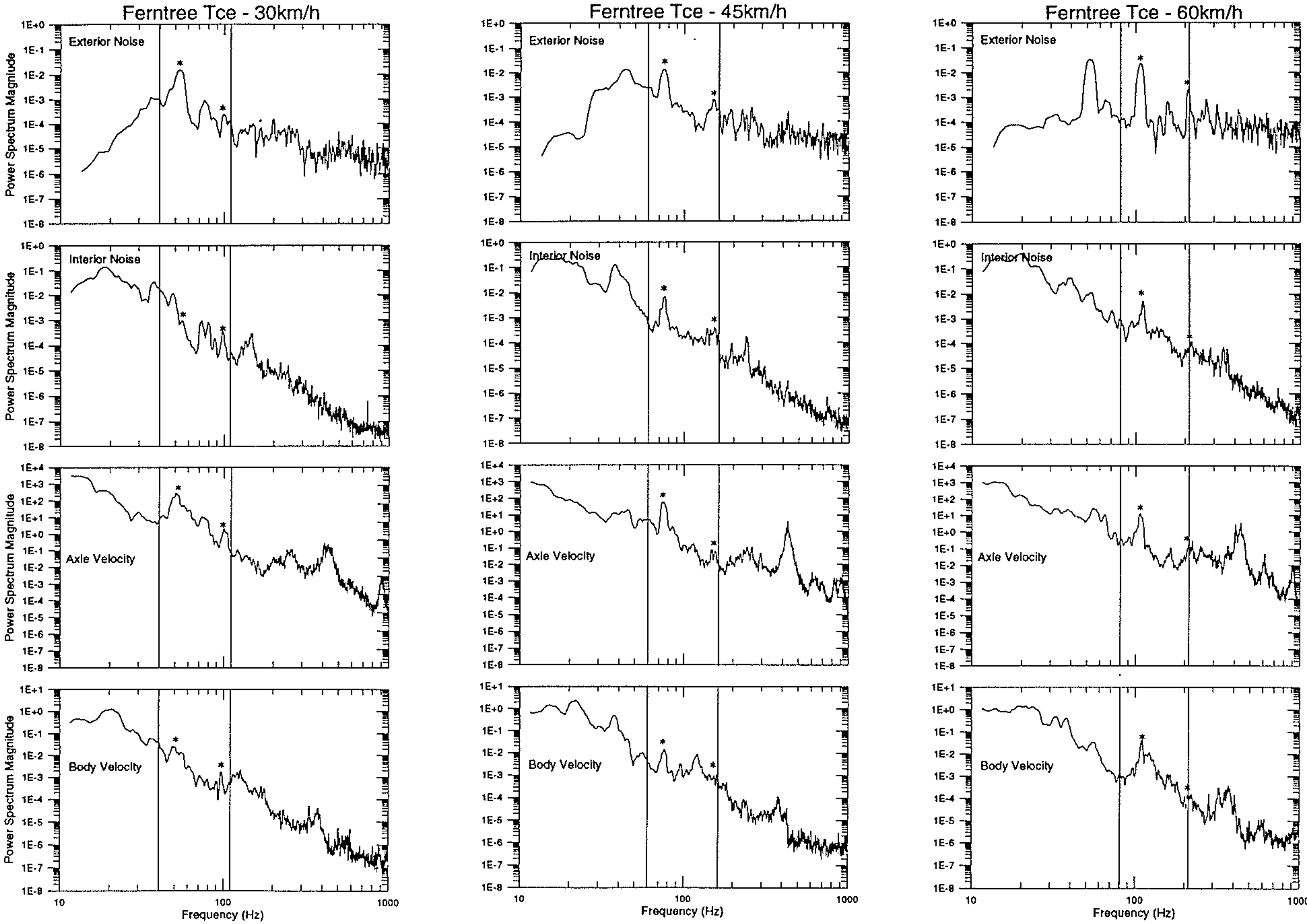


Figure A3.4 Continuous frequency spectra for concrete block pavers in Ferntree Terrace, Auckland, for vehicle speeds of 30 km/h, 45 km/h and 60 km/h.



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